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TITLE: Beam homogenizer and laser irradiation apparatus

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Abstract Text - ABTX (1):

There is provided a beam homogenizer which can unify the energy distribution of a **linear laser** beam in a longitudinal direction. In the beam homogenizer including cylindrical lens groups for dividing a beam, and a cylindrical lens and a cylindrical lens group for condensing the divided beams, the phases, in the longitudinal direction, of linear beams passing through individual cylindrical lenses of the cylindrical lens group for condensing the divided beams are shifted, and then, the beams are synthesized, so that the intensity of interference fringes of the linear beam on a surface to be irradiated is made uniform.

Brief Summary Text - BSTX (9):

Particularly, when a **linear laser** beam is used, unlike the case of using a spot-like laser beam which requires back-and-forth and right-and-left scanning, laser irradiation to the whole surface to be irradiated can be made by scanning in only the direction perpendicular to the line direction of the **linear laser**. Thus, high mass productivity can be obtained. The reason why scanning is made in the direction perpendicular to the line direction is that it is the most effective scanning direction. Because of this high mass productivity, at present, in the laser annealing, it has become the mainstream to use the **linear laser** beam obtained by processing the excimer laser beam through a suitable optical system.

Brief Summary Text - BSTX (10):

Recently, a **continuous-wave** laser, such as an Ar laser, having a higher output has been developed. There is also a report that an Ar laser was used for annealing of a semiconductor film and an excellent result was obtained. In this case, since the output of the Ar laser is not sufficient, an irradiation surface has a spot shape.

Brief Summary Text - BSTX (12):

Since the **continuous-wave** argon laser has a wavelength of about 500 nm, the absorption coefficient of the argon laser to a silicon film is about 10.sup.5 /cm. On the other hand, since the excimer laser is ultraviolet light of 400 nm or less, the absorption coefficient is about 10.sup.6 /cm which is higher than the argon laser by one digit. Thus, in the argon laser, the intensity is decreased to 1/e (e is a natural logarithm) at the point when the light travels 100 nm through the silicon film, while in the excimer laser, the intensity is decreased to 1/e at the point when the light travels 10 nm through the silicon film.

Brief Summary Text - BSTX (21):

In the homogenizer of FIGS. 25A and 25B, the dividing directions of the beam in the cylindrical lens groups 12 and 13 cross at right angles, and the condensing directions of the beam in the cylindrical lenses 14 and 16 cross at right angles. The intensity distribution of the **linear laser** beam 19 in the longitudinal direction is unified by the combination of the cylindrical lens group 12 and the cylindrical lens 16. The intensity distribution of the **linear**

laser beam 19 in the width direction is unified by the combination of the cylindrical lens group 13 and the cylindrical lens 14. That is, the beam is divided two-dimensionally and is again synthesized, so that the energy of the linear beam is unified.

Brief Summary Text - BSTX (22):
Thus, it appears that as the number of beams divided by the cylindrical lens groups 12 and 13 becomes large, the distribution of energy becomes uniform. However, irrespective of the fineness of division, stripe patterns of irradiation traces of the **linear laser** beam were formed on the silicon film. As shown in FIG. 24A, the countless stripe patterns appear to be orthogonal to the longitudinal direction of the **linear laser** beam (scanning direction of the linear beam, direction of GH), and peaks appear periodically on the silicon film as shown in FIG. 24C. It is expected that the cause of the stripe patterns is either one of the beam before it is incident on the beam homogenizer and the optical system of the beam homogenizer.

Brief Summary Text - BSTX (25):
An object of the present invention is to solve the foregoing problem of interference of beams having equal phases, such as laser light, and to unify the energy distribution of the **linear laser** light in the longitudinal direction.

Brief Summary Text - BSTX (31):
When the phases of the plurality of **linear laser** beams in the longitudinal direction are shifted by a predetermined size and are synthesized, the intensity of the interference fringes on the irradiated surface of the linear beams can be made uniform, as shown in FIGS. 28A-28C and 29A-29D explained later.

Brief Summary Text - BSTX (36):
The homogenizer of the invention shows remarkable effects in the case where coherent beams are linearly shaped, and the light intensity of the linear beam in the longitudinal direction can be smoothed. As a light source of the coherent light, a laser apparatus such as a gas laser or solid laser is used. A **continuous-wave** argon laser apparatus or pulse oscillation type excimer laser apparatus may be used.

Brief Summary Text - BSTX (37):
As the gas laser, an excimer laser may be named. Although the excimer laser is widely recognized as a pulse oscillation type laser, a **continuous-wave** excimer laser oscillation apparatus has been developed recently. In order to make continuous light emission, a microwave is used to accelerate excitation of an oscillation gas.

Brief Summary Text - BSTX (38):
By irradiating the microwave of the order of giga hertz to the oscillation gas to promote a rate determining reaction of oscillation, it has become possible to make continuous light emission of the excimer laser. The excimer laser having a high absorption coefficient to a silicon film becomes more and more important for crystallization of a semiconductor film when a **continuous-wave** one is put into practical use. When the **continuous-wave** excimer laser is used, irradiation traces of a pulse laser can be eliminated, so that the effect of laser irradiation processing can be greatly made uniform.

Drawing Description Text - DRTX (14):
FIG. 13 is a view showing an optical system for forming a **linear laser** of Embodiment 4;

Drawing Description Text - DRTX (15):
FIG. 14 is a view showing a scanning method of the **linear laser** of Embodiment 4;

Detailed Description Text - DETX (4):
FIG. 26 schematically shows the state of light interference fringes of the **linear laser** beam 19 formed by the beam homogenizer of FIGS. 25A and 25B. In FIG. 26, the vertical axis indicates laser intensity I. As shown in the drawing, a peak 302 in laser intensity periodically appears in a **linear laser** beam 301. This peak 302 is the interference fringe.

Detailed Description Text - DETX (6):
As shown in FIG. 26, in the beam homogenizer of FIG. 25, three waves are formed per period in the longitudinal direction of the **linear laser** beam 19. The number n of waves (which can be said to be the number of bright lines of the interference fringes in one period) and the number s of lenses of the cylindrical lens group 12 satisfy the following equation.

Detailed Description Text - DETX (8):
The present inventor calculated the relation between the shape of the wave of the linear beam in the longitudinal direction at some time of the **linear laser** beam and the number s of lenses through a computer. FIGS. 27A and 27B show the calculation results. FIG. 27A shows a case of S=7 and n+3 , and FIG. 27B shows a case of s=8 and n=4.

Detailed Description Text - DETX (9):
In FIGS. 27A and 27B, the horizontal axis indicates the phase (position) of a **linear laser** beam in the longitudinal direction, and the vertical axis indicates the amplitude of a wave. The square of the amplitude (value of the vertical axis) becomes the intensity of light (degree of strengthening of light beams with the same phase). Reference character d designates a length of one period and designates an interval between brightest lines of the interference fringes. The interference of the wave of FIG. 27A corresponds to FIG. 26, and the character d becomes an interval of the peaks 302 having the highest intensity.

Detailed Description Text - DETX (10):
FIGS. 27A and 27B show the results of computer simulation, and in an actual **linear laser** beam, the contrast in the light intensity does not become clear as in the simulation. It is inferred that this is caused by a subtle shift of an optical system, a material of an optical member, a working error, dispersion of energy due to thermal conduction in a semiconductor film, and the like. The difference in the magnitude of the intensity of the actual laser light is as shown in FIG. 24B.

Detailed Description Text - DETX (11):
In FIGS. 25A and 25B, the cylindrical lens 16 is divided into two portions by a broken line 20, and when an optical axis (principal point) is shifted in the direction perpendicular to the paper surface in the side view, a beam passing through a cylindrical lens 16a of an upper half of the cylindrical lens 16 and a beam passing through a cylindrical lens 16b of a lower half thereof are superimposed on each other while being shifted suitably on the irradiated surface, so that the pattern of the interference fringes is changed. That is, the intensity (energy) distribution of the **linear laser** beam in the longitudinal direction is changed. When this phenomenon is skillfully used, from the principle of superposition of waves, the light intensity can be smoothed by optimizing the shift distance of the divided cylindrical lenses 16a

and 16b.

Detailed Description Text - DETX (12):
The present invention uses this phenomenon to design a beam homogenizer. For that purpose, parameters of the beam homogenizer were changed and the change of the waveform of the **linear laser** beam was simulated by a computer. FIGS. 28A to 28C and FIGS. 29A to 29D show the results of the simulation. Similarly to FIG. 27, the graphs of FIGS. 28A to 28C and FIGS. 29A to 29D show the relation between the phase of the **linear laser** beam at some time in the longitudinal direction and the light intensity. FIGS. 28A to 28C show a case where the number s of lenses of the cylindrical lens group 12 of the beam homogenizer of FIG. 25 is 7, and FIGS. 29A to 29D show a case where the number s of lenses is 9.

Detailed Description Text - DETX (21):
Thus, when the phases of the laser beams divided by the cylindrical lens group 13 are shifted and are superimposed to the same irradiation position, it is possible to form a **linear laser** beam with a uniform energy distribution in the longitudinal direction as shown in FIGS. 28C or 29D.

Detailed Description Text - DETX (37):
In order to measure the period d of the interference fringes, in the cylindrical lens group 206, only one cylindrical lens 206a is made unchanged, and a **linear laser** beam is directly observed in the state where light does not pass through the other cylindrical lens 206b, and the period is measured. Besides, the period can be indirectly measured through an annealing effect by the **linear laser** beam. For example, as is explained by use of FIGS. 24A-24C, vertical stripes appear on a silicon film irradiated with a **linear laser** beam, and an interval of the vertical stripes may be measured. Besides, as described later, it is also possible to obtain the period through a simple calculation equation.

Detailed Description Text - DETX (54):
The embodiment mode of the invention becomes especially effective in the case where a rectangular laser beam in which its aspect ratio is not very large, is processed into a **linear laser** beam having an aspect ratio of 100 or more.

Detailed Description Text - DETX (61):
As is apparent from the above explanation, it is preferable that the period d of the interference fringes is constant in the **linear laser** beam. That is, it is preferable that the interference fringes appear at a constant period as shown in FIGS. 27A or 27B along the longitudinal direction of the linear beam.

Detailed Description Text - DETX (66):
As described above, when the invention disclosed in the present specification is used, the energy distribution of the **linear laser** beam in the longitudinal direction is remarkably made uniform. Particularly, in the case where the number of lenses constituting the cylindrical lens group 202 is an odd number, since the waveform of the **linear laser** beam in the longitudinal direction can be shaped into a sine state (see FIGS. 28C and 29D), the invention can most effectively function.

Detailed Description Text - DETX (68):
At such a time, when the scanning direction of the laser beam is finely adjusted, the improvement can be made. The fine adjustment is carried out by performing laser processing while the **linear laser** beam is scanned in the direction shifted by an angle y in a plane from the direction perpendicular to

the linear direction of the beam and containing the surface formed by the **linear laser** beam. This angle y can be found in the range of .vertline.tan y.vertline..ltoreq.0.1 (however, .vertline.tan y.vertline.-0).

Detailed Description Text - DETX (92):
The optical system 902 is an optical system on the optical path from the cylindrical lens group 202 to the cylindrical lens group 206 shown in FIG. 1. The mirror 207 and the cylindrical lens 208 are also based on the structure shown in FIG. 1. As any **linear laser** beam used in the invention, what is based on the optical system shown in FIG. 1 is used. The role of a lens group of a type as in FIG. 1 will be described below.

Detailed Description Text - DETX (95):
In the case of this embodiment, a period of optical interference fringes distributed in the **linear laser** beam formed through one lens 206a arbitrarily selected in the cylindrical lens group 206 and lenses other than the cylindrical lens group 206 in FIG. 1 was 0.1 mm. This value corresponds to the parameter d used in the invention.

Detailed Description Text - DETX (98):
That is, when the principal points of the cylindrical lenses 206a and 206b are shifted in the direction perpendicular to the optical axis, both ends of the **linear laser** beam 210 in the longitudinal direction become blur correspondingly to the shifted distance (see FIG. 2. White portions at both ends indicate the blurred portions). Since it is easy to make both ends of the **linear laser** beam in the longitudinal direction element regions, the slight blur does not influence the processing at all. On the other hand, since both ends in the width direction are not blurred at all, even if the element region is irradiated therewith, a bad influence does not occur.

Detailed Description Text - DETX (99):
Since n is equal to 3 in this embodiment, by this, the division number of the laser beam in the vertical direction (width direction of the linear beam) is determined by a multiple of (3-1). In the case of this embodiment, N was made 4, and division into 8 parts was made. The division number of the laser beam in the horizontal direction (longitudinal direction of the linear beam) is (2.times.3+1)=7. The beam emitted from the laser apparatus 201 is divided into 8 parts in the vertical direction (width direction of the **linear laser** beam) and 7 parts in the horizontal direction (longitudinal direction of the **linear laser** beam).

Detailed Description Text - DETX (100):
The **linear laser** beam 210 is one obtained by synthesizing 56 (=7.times.8) divided beams. By doing so, the energy distribution of the beam is smoothed.

Detailed Description Text - DETX (102):
The substrate 904 to be treated is disposed on a stage 905. The stage 905 can be moved in a one-axial direction by a moving mechanism 903. In actual processing, the stage 905 is moved in parallel to the vertical direction (including a plane containing the **linear laser** beam) to the line width direction of the **linear laser** beam.

Detailed Description Text - DETX (106):
In FIG. 5, a **linear laser** beam irradiated onto the treated substrate 904 is made 0.4 mm in width.times.135 mm in length.

Detailed Description Text - DETX (107):

The energy density of the laser beam on the surface to be irradiated is within the range of 100 mJ/cm.sup.2 to 500 mJ/cm.sup.2, and is made, for example, 300 mJ/cm.sup.2. The irradiation is made while the stage 905 is being moved in one direction at a speed of 1.2 mm/s, so that the **linear laser** beam is scanned. The oscillation frequency of the laser is made 30 Hz, and when attention is paid to one point of the irradiated object, laser beams of 10 shots are irradiated. The number of the shots is suitably selected from the range of 5 shots to 50 shots.

Detailed Description Text - DETX (111):
In this embodiment, although the **linear laser** beam is used, even when any beam shape from a linear shape to a square shape is used, the effect of the present invention is obtained.

Detailed Description Text - DETX (116):
In the case where the stripe pattern does not disappear well in the embodiment 1, the arrangement of the optical system is not suitable, or the way of superposition of the **linear laser** beams is unsuitable. In this case, the scanning direction of the substrate is finely adjusted by a scanning direction changing apparatus 906, and the scanning direction in which the interference fringes are less noticeable is selected.

Detailed Description Text - DETX (117):
That is, it is appropriate that laser light is made to be scanned and irradiated with a slight angle to the width direction of the **linear laser** beam.

Detailed Description Text - DETX (130):
Thus, if the focal distance f of the cylindrical lens 1206, the width L of one lens of the cylindrical lens group 202, and the wavelength .lambda. of the laser light are known, even if the period d of the interference fringes of the **linear laser** is not actually measured, it can be obtained through the calculation.

Detailed Description Text - DETX (134):
In the foregoing embodiment, although the pulse oscillation type excimer laser is used, in this embodiment, a **continuous-wave** excimer laser is used. In the case of the **continuous-wave** type, as compared with the pulse oscillation type, since a scanning speed of **linear laser** becomes slow, heat of laser light is apt to be conducted to a substrate. Thus, it is desirable that a quartz substrate having a high distortion point temperature is used as the substrate. The quartz substrate is not deformed or transformed at all even if it is heated up to the melting point temperature of a silicon film. Thus, a beam size can be widened.

Detailed Description Text - DETX (135):
In this embodiment, a description will be made on an example in which a **continuous-wave** excimer laser of 1000 W is processed into a linear beam (size of 125 mm.times.0.4 mm) and is used. FIG. 13 shows a structure of a beam homogenizer of this embodiment. The beam homogenizer of FIG. 13 corresponds to that of FIG. 1 in which the slit 205 is omitted. A cylindrical lens group 407 corresponds to the cylindrical lens group 202, a cylindrical lens group 408 corresponds to the cylindrical lens group 203, a cylindrical lens 409 corresponds to the cylindrical lens 204, and a cylindrical lens group 410 corresponds to the cylindrical lens group 206.

Detailed Description Text - DETX (138):
Similarly to the embodiment 1, the combination of the cylindrical lens group 407 and the cylindrical lens group 410 has a function to unify the distribution

of the intensity of the **linear laser** beam in the longitudinal direction, and the combination of the cylindrical lens group 408 and the cylindrical lens 409 has a function to unify the distribution of the intensity of the **linear laser** beam in the width direction.

Detailed Description Text - DETX (139):
By the combination of the cylindrical lens group 408 and the cylindrical lens 409, a beam with a beam width w is temporarily formed. It is possible to obtain a thinner (thinner than the beam width w) **linear laser** beam by arranging a doublet cylindrical lens 412 through the mirror 411.

Detailed Description Text - DETX (142):
When the section of the energy distribution of the **linear laser** beam formed by the optical system of FIG. 13 is seen in the width direction, a rectangular distribution was shown. That is, it was possible to obtain the **linear laser** beam having very high uniformity as to the energy density.

Detailed Description Text - DETX (147):
The linear **continuous-wave** excimer laser beam processed into the above size is scanned by a method as shown in FIG. 14, so that the whole surface of a silicon film is crystallized. Since the long side of the **linear laser** beam is longer than the length of the short side of the silicon film, the whole surface of the substrate can be crystallized by carrying out scanning once. In FIG. 14, reference numeral 401 designates a substrate; 402, a source driver region; 403, a gate driver region; and 404, a pixel. As is understood from FIG. 14, by merely scanning the **linear laser** beam 405 once in one direction, the whole silicon film is crystallized.

Detailed Description Text - DETX (151):
In this embodiment, a description will be made on an example in which a **continuous-wave** excimer laser oscillation apparatus is made a light source and a multiple substrate as set forth above is irradiated with a **linear laser** beam. In this embodiment, the size of the multiple substrate is made 600 mm.times.720 mm.

Detailed Description Text - DETX (152):
Although various methods are conceivable as a method of irradiating the multiple substrate with a **linear laser** beam, in this embodiment, a typical one is taken up and will be described.

Detailed Description Text - DETX (153):
A method used in this embodiment is shown in FIG. 15. A laser light emitted from a **continuous-wave** excimer laser oscillation apparatus 1301 is made a **linear laser** beam 1304 at an irradiation surface (substrate 1306) through an optical system 1302 and a mirror 1303. As the optical system 1302, one shown in the previous embodiment, for example, one shown in FIG. 13 is used.

Detailed Description Text - DETX (155):
Since the length of the **linear laser** beam formed by the optical system shown in FIG. 13 is 125 mm, it is longer than the length of one side of the region (square of 120 mm) occupied by one panel. Thus, only by scanning the **linear laser** beam once in one direction, the region for one column of panels can be treated. Since panels of 6 rows and 5 columns are arranged on the multiple substrate 1306, the whole surface of the substrate can be irradiated with laser by carrying out scanning 5 times. The scanning of the substrate is carried out by moving an XY stage 1305 movable in two orthogonal directions. The scanning direction of the substrate is made, for example, the direction indicated by an

arrow of a dotted line in FIG. 15.

Detailed Description Text - DETX (157):
In this embodiment, a description will be made on another example in which a multiple substrate is irradiated with a **linear laser** beam from an optical source of a **continuous-wave** excimer laser oscillation apparatus. In this embodiment, the size of the multiple substrate is made 600 mm.times.720 mm.

Detailed Description Text - DETX (158):
A method used in this embodiment is shown in FIG. 16. A laser light emitted from a **continuous-wave** excimer laser oscillation apparatus 1401 becomes a **linear laser** beam 1404 at an irradiation surface (substrate 1406) through an optical system 1402 and a mirror 1403. As the optical system 1402, one shown in the previous embodiment, for example, one shown in FIG. 13 is used.

Detailed Description Text - DETX (160):
Since the length of the **linear laser** beam formed by the optical system shown in FIG. 13 is 125 mm, it is longer than the length of one side when the above four panels are arranged by 2 rows and 2 columns (square of 120 mm). Thus, by only scanning the **linear laser** beam once in one direction, a region for panels of two columns can be treated.

Detailed Description Text - DETX (162):
As the length of the **linear laser** beam becomes long, or the panel becomes small, the number of columns of panels which can be subjected to laser irradiation by one scan of the **linear laser** beam increases. According to the length of the **linear laser** beam and the panel size, three columns of panels or more can be subjected to laser irradiation by one scan of the **linear laser** beam.

Detailed Description Text - DETX (166):
First, as a substrate, a quartz substrate 701 is prepared. The reason why the quartz substrate is used is that a **continuous-wave** excimer laser is used as means for crystallization. A silicon oxide film (also called a base film) 702 having a thickness of 200 nm and an amorphous silicon film 703a having a thickness of 55 nm were continuously formed thereon without exposing to the air (FIG. 17A). By doing so, it is possible to prevent an impurity contained in the air, such as boron, from being adsorbed to a lower surface of the amorphous silicon film 703a.

Claims Text - CLTX (99):
11. An apparatus according to claim 6, wherein the laser generating apparatus generates a **continuous-wave** excimer laser beam.

Claims Text - CLTX (107):
14. An apparatus according to claim 7, wherein the laser generating apparatus generates a **continuous-wave** excimer laser beam.

Claims Text - CLTX (108):
15. An apparatus according to claim 8, wherein the laser generating apparatus generates a **continuous-wave** excimer laser beam.

Claims Text - CLTX (109):
16. An apparatus according to claim 9, wherein the laser generating apparatus generates a **continuous-wave** excimer laser beam.